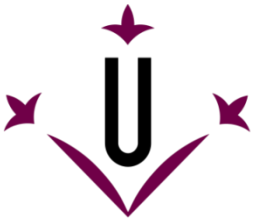

Effect of substituting barley with sorghum on starch digestion, rumen microbial yield and growth in Iranian Baluchi lambs fed high concentrate diets

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Abstract

This study investigated the effects of substituting barley (B) with sorghum (S) on site and extent of *in vivo* disappearance of dry matter (DM), starch and nitrogen in the gastro- intestinal tract (GIT), microbial protein synthesis and growth in finishing lambs. 18 male Iranian Baluchi lambs were randomly allocated to three dietary treatments in a complete randomized design (CRD). Dietary grain treatments were: barley (B) as control, barley: sorghum (BS) (in equal amount) and sorghum (S). At the end of the feeding trial, the lambs were euthanized and digesta contents in the different sections of the GIT were collected to determine DM, starch and nitrogen disappearance. Starch intake of lambs on barley (B) diet was lower than those fed S and BS but lambs on B diet had higher ($P<0.05$) ruminal DM con- tent and starch disappearance resulting in lower ($P<0.05$) ruminal pH than those fed diets containing sorghum. Although lambs on B diet had higher ($P<0.05$) volatile fatty acids (VFA) concentration in the rumen, highest ruminal microbial protein synthesis was recorded in lambs fed BS diet, presumably due to the more synchronized release of energy and nitrogen together with the higher rumen pH appropriate for microbial growth. Although a higher ($P<0.05$) outflow rate (g/d) of starch into the small intestine was observed for high sorghum (S) diet than the BS and control (B) diets, lambs on S diet had the lowest microbial-N flow to small intestine, resulting in the lowest N and starch digestibility in the small intestine and total track. There was a clear positive relationship between microbial N (MN) synthesis and starch disappearance in the small intestine, with BS lambs producing the highest and S lambs lowest MN yield (32.2 and 24.1 g/d, respectively) and corresponding starch disap- pearance was 0.87 and 0.58, respectively. The majority of the post-ruminal nutrients (DM, N and starch) were hydrolyzed in the distal-duodenum and anterior segments of jejunum.

It can be concluded that substitution of barley with 0.50 sorghum increased outflow of starch from the rumen, enhanced starch digestibility and absorption in

the small intestine and resulted in higher growth rate as evident by the higher average daily gain (ADG) and more efficient feed conversion ratio (FCR) recorded for lambs on the BS diet.

Keywords: Digesta outflow, Lamb, Post-ruminal, Ruminal, Small intestine, Starch degradability

Introduction

The native medium-sized Baluchi sheep, making up about 30% of the total Iranian sheep population is well adapted to the arid and semi-arid climates of eastern Iran (Razmi et al., 2002; Khan et al., 2007; Tahmoorespur et al., 2010). Contin- uous decline in productivity of pasturelands and increased demand for mutton forced sheep producers to switch from the traditional ranging to more intensive production systems based on concentrate feed with locally produced barley grain as the principal energy source. It is well documented that barley starch is quickly fermented (Horadagoda et al., 2008) which could lead to increased rumen dysfunctions such as acidosis (Galyean and Rivera, 2003). Extensive research has also shown that feeding a mixture of cereal grains of differing fermentation rates could reduce excessive rumen VFA production, pre- venting rapid drop in ruminal pH resulting in better rumen function and animal performance (Allen, 1997; Khorasani et al., 2001; Haddad and Nasr, 2007; Lehmann and Meeske, 2007). Sorghum (*Sorghum bicolor L. Moench*) reported to contain starch highly resistant to rumen microbial breakdown (Offner et al., 2003) could thus be an appropriate alternative energy source to replace barley for lambs production in Iran (Yahaghi et al., 2012).

In recent years there is an increased cultivation of sorghum in Iran because of its better ability to adapt to the harsh arid environment than barley (Wong et al., 2009; Beheshti, 2010). However, little is known on the use of sorghum as energy source in Iranian Baluchi lambs production except that partial substitution of barley with low degradability source such as sorghum improved animal performance (Yahaghi et al., 2012). The improved performance may be due to increased outflow of rumen undegraded starch to the small intestine leading to a more efficient starch digestion (Harmon and McLeod, 2001; Reynolds, 2006).

The aim of the present study was to determine the effects of partial and full substitutions of barley with sorghum on rumen fermentation characteristics,

intestinal starch digestion, microbial protein synthesis and growth in Iranian Baluchi lambs fed high cereal diets.

Materials and methods

Animals and experimental diets

This study was conducted at the Abbas Abad Baluchi Breeding Station, northeast of Mashhad, Iran. 18 weaned male Baluchi lambs (65 days of age and 31 ± 1.9 kg live weight) were randomly assigned to three dietary treatments (6 lambs per diet) in a complete randomized design feeding trial. Three iso-caloric and iso-nitrogenous experimental diets (32.5/67.5 Alfalfa hay: concentrate ratio) were formulated. Composition of alfalfa was 880, 160 and 430 (g/kg) for DM, CP and NDF respectively. The ingredient and chemical compositions of the concentrates are detailed in Table 1. Alfalfa was long/chopped and mixed with the concentrates. Barley (*Hordeum* spp.) was the main energy source for the control concentrate (B) and was substituted partially (0.50, BS) or fully (S) with sorghum (*Sorghum bicolor* L. Moench), respectively. Animals were cared according to the experimental protocols and approved for animal research by the Ethical Committee of University Ferdowsi of Mashhad, Iran (Code 1829).

Experimental procedure and samples collection

Feeding and digestibility trials

After a week of adjustment to the diets, the study lasted for 77 days and consisted of a feeding (d1 to d65) and a digestibility (d65 to d75) trial and after that animals were euthanized in order to determine nutrient absorption kinetics in the gut (d75 to

d77). During the feeding trial lambs were housed in individual pens (1.5 m × 2 m) and fed twice a day (08:00 and 16:00 h) *ad libitum* the assigned experimental diets (see Section 2.1). Animals had free access to clean drinking water and they were weighed weekly before the morning feeding. For the digestibility trial lambs, were moved to individual metabolism cages (1.5 m × 0.75 m) maintaining the feeding regime but feed was offered 4 times at 6 hourly intervals per day. The digestibility trial consisted of a 3-day adaptation followed by 7-day total collection of feces and urine. Daily urine output was collected in an acidic solution, pH < 3 (100 ml of 1 M H_2SO_4) to prevent bacterial contamination. The urine was weighed, sampled (100 g/kg) and pooled on individual animal basis over 7 days and stored at −20 °C for further analyses.

Nutrients disappearances through the intestine

Ytterbium (Yb) acetate was used as a digesta flow marker and individual daily doses of 2 mg Yb/kg LW were diluted in dis- tilled water (20 ml) and dosed orally 4 times a day (5 ml/time) after feeding during the 7-day digestibility trial. Immediately after the trial lambs were randomly divided in two groups and euthanized the next two days to determine DM, starch and N disappearance through the intestinal tract. Two hours after feeding and with approximately 30-min interval, lambs were intramuscularly anesthetized (Xylazine, 0.3 mg/kg LW, Calier Laboratories, Barcelona, Spain) prior to intravenous euthanati- zation (Thiopental, 10 mg/kg LW Calier Laboratories, Barcelona, Spain). The digestive tract was then dissected and to prevent further digesta mixing, intestinal segments were tied with cotton threads around the tissue before the intestine was released from the mesentery and sectioned to individual segments. Beside the reticulo-rumen and abomasums, the small intestine was sub-divided into 1-m segments starting from the pylorous. Before slaughtering, blood samples were taken from portal and jugular veins using heparinzed vacuum tubes. Blood samples were then centrifuged at 2500 × *g* for 20 min at 4 °C and the plasma was stored at −20 °C.

The rumen was opened, pH of rumen content was immediately recorded, and total digesta content was taken, homogenized and strained through two layers of cheesecloth and three samples were taken; 100 g rumen digesta to determine DM, organic matter (OM), N, starch and Yb while two (4 ml) additional samples were taken from the filtrate for ammonia and volatile fatty acid (VFA) analysis. For the latter, 0.6 ml of meta-phosphoric acid (240 g/L) in 1.5 M H_2SO_4 (8.47 ml of concentrated H_2SO_4 diluted to 100 ml with distilled water) was added to 3 ml of rumen fluid. After standing overnight at room temperature the supernatant (0.5 ml) was added to 0.5 ml of 20 mM 4-methyl-*n*-valeric acid (internal standard) and samples were frozen (−20 °C) for further analyses. Total abomasal digesta content was also collected, homogenized and sampled. In the lower intestine, digesta samples were taken from duodenum: proximal (from 0 to 1 m) and distal (from 2 to 4 m), from jejunum: proximal (from 4 to 6 m) and distal (from 6 to 8 m) and from the distal ileum (last meter of the small intestine). Digesta were gently removed and individually kept in containers, frozen and freeze dried immediately. Feces were also homogenized and sampled.

Chemical analyses

DM was determined by drying samples to constant weigh at 105 °C and OM by combustion at 550 °C for 8 h in a muffle furnace. NDF concentration was determined without using heat-stable alpha-amylase and sodium sulphite and NDF was expressed inclusive of residual ash (Van Soest et al., 1991; AOAC, 2005). Total N in feed, refusals and digesta was determined following the Kjeldahl method (Kjeldahl unit Vapodest 30, C. Gerhardt, GmbH & Co., KG, Königswinter, Germany, AOAC index no. 977.02). NH_3-N in digesta was determined by Kjeldahl method without applying acid hydrolysis. Non-ammonia N (NAN) in abomasal digesta was assayed by the same method after removing the ammonia with 1 M NaOH. Volatile fatty acid (VFA) concentration in deproteinized rumen fluid was determined by gas chromatography (GC) following the protocol of Jouany (1982).

Yb in digesta samples was determined by spectrophotometry following the protocol of Hart and Polan (1984). Urinary purine derivatives (PD; i.e. allantoin, uric acid, xanthine and hypoxanthine) concentrations were analyzed following the methods proposed by Balcells et al. (1992). Starch was converted to soluble carbohydrates after cx-amylase treatment followed by re-incubation with amyloglucosidase as described by Horadagoda et al. (2008). Concentration of blood glucose and blood urea nitrogen (BUN) were analyzed following the method of Kaneko (1989).

Calculations and statistical analyses

Rumen microbial N production was calculated from urinary PD excretion rate following the model proposed by Chen and Gomes (1995). The post-ruminal flow of DM (DMf) in different parts (*i*) of the intestinal tract was calculated using DM and Yb concentration in digesta samples:

$$DMf_i = \frac{DM(i,g) \times Yb\ (i, mg)}{\text{Daily Yb doses (mg/d)}}$$

Apparent and true nutrients disappearance from the different segments of the gut tract was calculated assuming no Yb absorption though the intestinal tract. Apparent digestibility of DM and other nutrients (starch and N) in the different intestinal tract parts (*i*) was calculated as follow:

$$\text{Apparent digestibility } (i \text{ part}) = \frac{(\text{g DM or nutrient } (i-1) - \text{g DM or nutrient } (i))}{\text{g DM or nutrient } (i\text{-}1)}$$

Statistical analysis was conducted using GLM procedure (SAS, 2003) using a complete randomized design following the model: $Y_{ij} = \mu + T_i + A_j\,(i) + \boldsymbol{\varepsilon}_{ij}$, where μ is the mean value, T_i is the treatment effect (fixed), $A_j(i)$ was the effect of animal nested within each treatment and $\boldsymbol{\varepsilon}_{ij}$, the error term. Differences in LSD were declared significant at P<0.05.

Results

Apparent ruminal and post-ruminal DM and starch disappearance through the gastro intestinal tract (GIT)

Dry matter (DM)

DM intake (DMI), DM flow through the different segments of GIT, disappearance and digestibility are presented in Table 2. Type of grain in the concentrates did not affect DMI, averaging 2026 g/d. Although ruminal DM disappearance with the B and BS diets was higher (P<0.05) than with the S diet, no differences were detected in apparent DM digestibility among treat- ments. In general, along the different segments of the small intestine, the bulk of DM was digested in the distal duodenum followed by the proximal jejunum and the remaining in the lower segments of the small intestine. Intestinal gut DM digestibility with the BS diet was higher than that with the B or S diet with total tract DM digestibility exhibiting a similar trend.

Starch

Apparent ruminal and post-ruminal starch flow, disappearance rates and digestability values are presented in Table 2. The low starch content in barley (Table 1) was reflected in the lower (P<0.05) starch intake (g/d) for B compared to BS and S diets. However, the amount of starch digested in the rumen (g/d) for B diet (714) was the highest followed by BS (659) and S (616), with corresponding apparent digestibility values of 0.80, 0.69 and 0.62, respectively (Fig. 1). Of the total starch entering the small intestine, a smaller quantity was digested with the B diet than with the BS or S diet.

Similar to DM disappearance data, bulk of starch along the small intestinal tract was digested in the distal duodenum and in postal jejunum (Fig. 1) and the remaining in the lower segments of

the small intestine. Starch disappearance (g/d) in the distal duodenum for BS diet was the highest (P<0.05) followed by S and B being the lowest (Fig. 1). It is worthy to mention that the amount of starch fermented in the hindgut (g/d) for S diet was approximately 6 times higher (P<0.05) than that for B and BS diets (Table 2) indicating the higher amount of the sorghum starch which resisted enzymatic digestion in the small intestine was fermented in the hindgut.

Nitrogen

Lambs fed the three dietary treatments had similar (P=0.8) N intakes, averaged 45 g/d but the contents of abomasal N in all treatments were higher than their respective N intake. The increase was highest for BS, followed by S and B diets (Table 3). No changes in urinary N although animals in the BS group retained more (P<0.05) N.

As mentioned above, along the small intestine, the majority of the N was digested in the distal duodenum and postal jejunum segments. The BS lambs recorded the highest (P<0.05) amount of N digested (g/d) in the small intestine compared to that in lambs fed B and S diets. Consequently, average total tract N disappearance and also N digestibility for BS diet were higher than the corresponding values for B and S diets. The origin of rumen N outflow was modified by the type of concentrate, with microbial N (MN) in lambs fed the BS diet higher (P<0.05) than B and S diets, whereas non-microbial N in S was higher (P<0.05) than BS and B. Microbial yield efficiency (g MN/kg DOMI) was also influenced by diet treatments with lambs on BS diet been most efficient followed by those in B and S.

Rumen characteristics and blood parameters

The type of cereal grain in the concentrate had a significant effect (P<0.05) on ruminal fermentation characteristics. Lambs fed barley (B) showed a lower (P<0.05) rumen-pH than those fed S and BS diets (Table 4). Rumen NH_3-N concentration (mg/100 ml) was not different between B and BS diets but was lower than that for the S diet.

Rumen VFA concentration in lambs fed B concentrate was higher (P<0.05) than that fed S diet, however, no differences were detected between BS with either B or S diets. Acetate proportion differed (P<0.05) among treatments, being highest for S and lowest for B diets. In contrast, propionate concentration was higher (P<0.05) in B diet compared to BS or S

diets. No differences were detected among treatments for butyrate concentration.

The concentration of individual VFA in the portal vein appeared to reflect that in the rumen liquor. The higher acetate and lower propionate in lambs fed S compared to those fed B or BS diets resulted in higher A/P ratio for lambs on S diets than those in the other two treatments. However, no differences were detected in total VFA concentration in the portal vein among treatments. Glucose concentration in the portal vein was greater ($P<0.05$) for BS diet than for B and S diets, whereas those in peripheral blood vein were not affected by experimental treatments although the concentration in BS (93.2 mg/dL) lambs tends to be higher than those in B with 79.2 and S with 80.0 mg/dL. Concentration of BUN in portal vein was modified by source of grain (18.1, 15.3 and 14.1 mg/dL for S, BS and B, respectively; $P<0.05$) and such differences were also evident in peripheral blood. BUN values in jugular vein differed ($P=0.03$) among treatments, with lambs fed S diet showing the highest value.

Growth performance

Initial, final weight, average daily gain (ADG) and feed conversion ratio (FCR) are shown in Table 5. Lambs fed the mixture of barley and sorghum (BS) achieved higher ($P<0.05$) ADG and a more efficient FCR than those fed barley or sorghum diets.

Discussion

Rumen DM and starch fermentation

Using barley grain as the main source of energy in the concentrate (diet B) resulted in lowest rumen pH (5.8) approaching the benchmark limit (pH 5.6 to 5.2) for chronic acidosis suggested by Cooper and Klopfenstein (1996) and lower than the corresponding values recorded for BS (6.23) and S (6.44). The above results reaffirmed previous findings (Mendoza et al., 1999; Khorasani et al., 2001; Offner et al., 2003; Fox et al., 2007; Horadagoda et al., 2008) that the high fermentation rate of barley starch has a negative effect on rumen environment resulting in reduced rumination (Owens et al., 1998; Horadagoda et al., 2008) and reduced growth and activity of cellulolytic microorganisms (Allen, 1997).

The high rate of starch fermentation of the barley diet was also reflected in the high concentration of VFA, which progres- sively decreased with the inclusion of sorghum (Table 4). The above observation was also reported by Surber and Bowman (1998) comparing barley with corn as slowly degradable source of starch in beef cattle. Acetate was the predominant VFA in all treatments, but barley enhanced the propionate concentration in detriment of acetate, although study by Rotger et al. (2006) could not establish such direct relationship.

The three iso-caloric, iso-nitrogenous diets were designed with fixed substitution rates of barley with sorghum grain. However, subsequent analyses indicated that due to the lower starch content in barley compared to sorghum, starch content in the B diet was lower than those of BS and S (Table 1). For that reason lambs on BS and S consumed 7 and 11% more starch, respectively, compared to the control (B) diet. However, of the total ingested starch by lambs on B diet, 0.81 was fermented (0.80 in rumen 0.012 in cecum) and only 0.16 digested in the lower gut with about 0.03 excreted via feces (Fig. 1). In contrast, the sorghum diet showed different digestion kinetics; only 0.65 was fermented (0.62 in rumen and 0.28 in cecum) with 0.22 digested in the small intestine and absorbed, presumably mostly as glucose. As expected, the corresponding values with the BS diet were in between the two, with 0.70 of the total ingested starch fermented (0.69 in rumen and 0.007 in cecum) and 0.27 which was the highest amount digested in the small intestine among all treatments.

Nitrogen fermentation and microbial protein synthesis

Mean rumen NH_3-N concentrations for all dietary groups were higher than 5 mg/100 ml, indicating that microbial growth was not limited by N availability (Kim et al., 2010) with lambs fed S diet showing higher ($P<0.05$) NH_3-N concentrations than those fed B and BS diets. Conventionally, the low ammonia levels in barley based diet has been related to the higher rate of starch degradability, energy availability and consequently NH_3-N incorporation into microbial cells (Duff et al., 2002; Rotger et al., 2006; Li et al., 2011); however, others found the opposite, i.e. greater rumen NH_3-N concentration in barley than in slow-degradable starch sources, such as corn in steers (Surber and Bowman, 1998).

In all treatments, rumen N outflow rates were greater than their respective N intake values (Table 3) which could indicate: (i) an overestimation of rumen N outflow based on the use of Yb as flow-marker in the study, (ii) endogenous N input into the rumen via urea recycling

and (iii) N input from microbial synthesis. As the recovery of the marker in the fecal-Yb was near complete (0.99), it seems that the N outflow values were not overestimated. Although N recycling was not measured in this study, N recycling was reported for steers (Richards et al., 2003; Kim et al., 2010), beef cattle (Milton et al., 1997) and goats (Soto-Navarro et al., 2003) fed various concentrate diets. However, N recycling alone can probably explain the 0.09 higher N outflow over N intake in the BS diet except for the difference due to N from rumen microbial synthesis.

Nucleic acids flowing out the rumen are essentially of microbial origin, which are efficiently digested with 0.92 of their purine bases absorbed (Chen et al., 1992) and which are subsequently partially metabolized and excreted as purine deriva- tives (PD) primarily through the kidney. Thus urinary excretion of PD reflects and can be used as an index of MN supply (Chen and Gomes, 1995). With the model proposed by Chen and Gomes (1995) the MN flow was estimated highest for BS followed by B and S. The values were within the range reported by Mota et al. (2008) for dairy goats. Lambs fed a mixture of barley and sorghum (BS) also recorded higher microbial growth efficiency compared to those in B and S diets.

Hypothetically, a better synchronized supply of energy and N as well as the relatively high rumen pH 6.23 of lambs fed BS diet could explain for the enhanced MN synthesis. The complex sorghum protein matrix restricts its accessibility to microbial digestion, reduces starch degradability (Andrade-Montemayor et al., 2009) and probably also energy availability for optimal microbial growth and efficiency. On the contrary, the fast fermentation rate of barley creates an unfavorable rumen environment, whereby the microbes need to increase their maintenance requirements to survive in such adverse environment (Van Kessel and Russell, 1996). Yang et al. (1997) and Philippeau et al. (1999) reported increased MN flow to the duodenum when wheat or barley was replaced by a slow source of rumen fermentable starch such as corn, however, we are not aware of any published data on the effect of substituting barley with sorghum on MN synthesis.

Post ruminal nutrient digestion

Because of the lower degradation rate in the rumen, sorghum grain increased the amount of starch flow into the small intestine and subsequently its digestion and absorption. Starch disappearance (absorption) rate in the small intestine with the BS diet was higher than with

the S and B diets (Table 2). However, total apparent digestibility in the small intestine was not consistent with disappearance data among the experimental diets with the lowest value registered with the S diet and the highest with the BS diet and B diet in between the two (0.80).

A low digestibility of sorghum grain diets has been previously documented (Firkins et al., 2001; Bowen et al., 2007) and the authors suggested that the reduction was influenced by several factors including grain processing or plant variety (Huck et al., 1998). All the grains used in this study were freshly ground without pre-processing, however, sorghum grain is known to contain anti-nutritive compounds (Svihus et al., 2005; Mahasukhonthachat et al., 2010; Al-Rabadi et al., 2011) which escape rumen fermentation (Zinn and Owens, 2008) and could inhibit the activity of cx-amylase (Svihus et al., 2005) on its starch digestion in the small intestine.

The process of intestinal starch assimilation begins in the lumen of the small intestine with the secretion and action of pancreatic cx-amylase. Harmon (2009), in his review, indicated that concentration and secretion of pancreatic cx-amylase can be manipulated nutritionally but the exact regulatory mechanisms in ruminants are lacking. Based on research data in the literature (Taniguchi et al., 1995; Richards et al., 2003; Swanson et al., 2008), it was clear that among other factors, secretion of cx-amylase is highly responsive to the presence of protein.

Interestingly, there was a clear positive relationship between flow of MN (but not total N) and starch disappearance in the small intestine in the present study. Mean values of MN synthesis for BS, B and S were 32.2, 28.2 and 24.1 g/d, respectively, and their correspondent values for starch digestibility (abomasal flow) in small intestine were 0.86, 0.80 and 0.58, respectively.

The above observation thus suggests that quality and not necessarily quantity of protein stimulates secretion of cx-amylase for starch digestion in the small intestine, which is in agreement with results of previous research (Swanson et al., 2008).

Kinetics of post-ruminal starch disappearance through the lower gut reflect that starch was mostly digested in the distal duodenum [0.38, 0.46 and 0.30 of abomasal flow (Fig. 1)] and reached a total small intestine digestibility of 0.80, 0.86 and 0.58, respectively for B, BS and S diets (Table 2). The above data also suggest that 0.42 of the abomasal starch in S diet was not digested in the small intestine and subsequently underwent less efficient caecal

fermentation or excreted in the feces (Fig. 2).

Blood parameters

The higher glucose concentrations in portal blood of lambs fed S and BS diets seem to indicate higher glucose absorption (coming from digested starch) in the portal drained viscera (PDV) compared to those with the B diet (Table 4). The above result correlates with the higher amount of starch digested in the small intestine for lambs fed S and BS diets over that for B diets, however, the above suggestion needs to be interpreted with caution as the values of glucose in portal blood represent a concentration and not an absolute quantity. Likewise, increases in glucose concentration in the portal vein were detected when slowly degradable cereal (corn) instead of barley was used (Cerrilla and Martínez, 2003).

Metabolism of VFA across the ruminal wall is substantial and the proportion of VFA appearing in the portal vein remains constant across a wide range of different diets (Seal and Reynolds, 1993). Similarity in the proportion of ruminal VFA and that recorded in the portal blood samples in the present study thus reaffirmed the above.

Animal performance

Improved ruminal, post-ruminal and thus total tract nutrients digestibility in lambs fed a mixture of barley and sorghum (BS) resulted in higher ADG and more efficient FCR. The present results are in agreement with previous studies (Huck et al., 1998; Mendoza et al., 1999; Haddad and Nasr, 2007; Lehmann and Meeske, 2007; Li et al., 2011) which reported that combinations of cereal grains enhance growth performance through associative effects among feeding ingredients on rumen fermentation. The improved growth performance could be due to several reasons; (i) more efficient rumen fermentation to prevent rapid decline in rumen pH and synchronized release of energy and N for better microbial synthesis and fiber fermentation, (ii) increased rumen bypass starch and digestion in the small intestine and possibly (iii) enhancing availability of intact amino acids which provided the animal with more essential amino acids for tissue synthesis (Yu et al., 2002).

Conclusion

Substituting 0.5 of the barley with sorghum in a high concentrate diet enhanced ruminal outflow and intestinal digestion of starch resulting in a higher growth rate. The low digestibility of sorghum starch in the small intestine resulted in a higher proportion of it to undergoing a less energetically efficient fermentation in the caecum and as waste in the feces in the complete barley substituted diet. One option to further increase the substitution rate of barley with sorghum could be by improving the potential digestibility of sorghum starch through mechanical treatment, such as extrusion.

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Table 1
Ingredients and chemical compositions of the concentrate diets.

Ingredients (g/kg DM)	Dietary treatments[a]		
	B	BS	S
Barley grain	840	420	0
Sorghum grain	0	420	840
Wheat bran	110	80	70
Cotton seed meal	30	60	70
Limestone	15	15	15
Mineral and vitamin mix[b]	5	5	5
Chemical composition (g/kg DM)			
Dry matter (g/kg fresh matter)	910	910	910
Starch	580	640	690
Crude protein	140	140	140
Organic matter	940	950	950
ME (MJ/kg DM)[c]	11.97	11.88	11.72

[a] Dietary treatment, with barley (B), barley/sorghum (BS, 50:50) and sorghum (S) as source of starch in the concentrates.
[b] Composition (mg/kg feed): 4.9 mg of Zn, 4.05 mg of Mn, 0.45 mg of Cu, 0.075 mg of I, 0.1 mg of Se, 2500 IU vitamin A, 400 mg of vitamin D, 2.5 IU vitamin E.
[c] ME, metabolizable energy, estimated from NRC (2007).

Table 2
Flow, apparent disappearance and digestibility of dry matter and starch in different parts of the intestinal tract in Baluchi lambs fed diets with different starch sources.

Diet component	Dry matter					Starch				
Diet[a]	B	BS	S	SEM[b]	P<	B	BS	S	SEM[b]	P<
Intake (g/d)	2022	2042	2015	40.1	0.9	890[b]	956[a]	993[a]	12.7	0.01
Flow (g/d)										
Abomasum	1125	1141	1170	8.9	0.07	176.6[c]	297[b]	377[a]	9.2	0.01
Ileum	687[a]	546[b]	692[b]	15.2	0.01	35[b]	40[b]	139[a]	3.7	0.01
Feces	605[a]	480[b]	620[a]	14.3	0.01	27[b]	33[b]	110[a]	4.8	0.01
Apparent disappearance (g/d)										
Rumen	897[a]	902[a]	842[b]	9.1	0.01	714[a]	659[ab]	616[b]	19.1	0.01
Small intestine	438[c]	594[a]	477[b]	10.8	0.01	141[c]	257[a]	218[a]	6.8	0.01
Large intestine	82.0	66.5	72.1	5.02	0.12	8.8[b]	7.3[b]	48.9[a]	2.42	0.01
Total	1417[b]	1562[a]	1395[b]	34.5	0.01	863[b]	923[a]	883[ab]	15.0	0.04
Apparent digestibility										
Rumen (intake)	0.44	0.44	0.42	0.911	0.17	0.80[a]	0.69[b]	0.62[a]	1.201	0.01
Small intestine (abomasal flow)	0.39[b]	0.52[a]	0.41[b]	1.020	0.01	0.80[b]	0.87[a]	0.58[c]	1.102	0.01
Large intestine (ileal flow)	0.12	0.12	0.10	0.772	0.21	0.25	0.19	0.31	3.850	0.10
Total (intake)	0.70[b]	0.77[a]	0.69[b]	0.652	0.01	0.97[a]	0.97[a]	0.89[b]	0.521	0.01

Means within a row with different letters differ ($P < 0.05$).
[a] Dietary treatment, with barley (B), barley/sorghum (BS, 50:50) and sorghum (S) as source of starch in the concentrates.
[b] Standard error of the difference of the means.

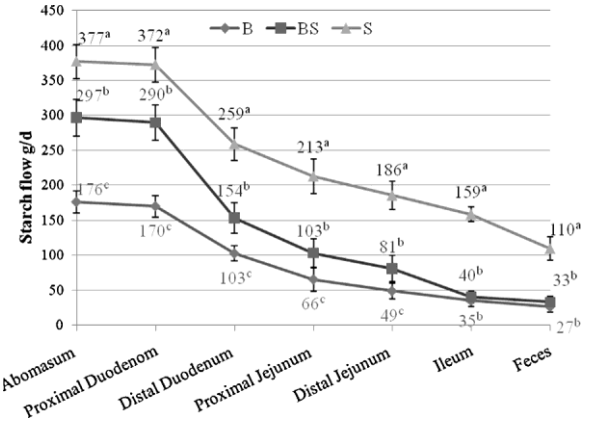

Fig. 1. Post-ruminal starch flow in Baluchi lambs feed diets with barley (B), barley–sorghum (BS) and sorghum (S) a,b,c: means in a segment with different superscripts differed significantly (P<0.05).

Table 3
N balance, digestibility and characteristics of duodenal flow in Baluchi lambs fed diets with different starch sources.

Item (g/day)	Dietary treatment[a]			SEM[b]	P<
	B	BS	S		
N intake	45	46	44	1.9	0.8
N excretion					
Urine	17.8	15.4	16.4	0.78	0.13
Feces	14.1[ab]	11.5[b]	16.3[a]	1.10	0.03
N balance	13.6[b]	18.9[a]	12.4[b]	1.50	0.02
N digestibility					
Rumen (intake)	1.01	1.09	1.05	2.610	0.14
Small Intestine (intake)	0.55 [b]	0.63 [a]	0.55 [b]	2.201	0.04
Apparent N digestibility	0.69[ab]	0.75[a]	0.64[b]	2.482	0.02
Total rumen N outflow (g/d)	45.8	49.4	47.3	1.59	0.30
Rumen MN outflow (g/d)	28.2[ab]	32.2[a]	24.1[b]	1.76	0.02
Rumen non-MN flow (g/d)	17.6[b]	17.2[b]	23.8[a]	1.59	0.02
MNE[c]	29.7[b]	37.7[a]	27.7[b]	1.71	0.01

Means within a row with different letters differ ($P < 0.05$).
[a] Dietary treatment, with barley (B), barley/sorghum (BS, 50:50) and sorghum (S) as source of starch in the concentrates.
[b] Standard error of the difference of the means.
[c] Microbial N efficiency (g MN/kg DOMI), (DOMI, digestible organic matter intake).

Table 4
Rumen characteristics and blood metabolites concentration in Baluchi lambs fed diets with different starch sources.

Item	Dietary treatments[a]			SEM[b]	P
	B	BS	S		
Rumen parameters					
pH	5.9[b]	6.23[a]	6.44[a]	0.082	0.01
NH_3 (mg/100 ml)	19.0[b]	19.7[b]	29.1[a]	1.39	0.01
VFA (mM)	101.2[a]	97.7[ab]	90.1[b]	2.61	0.03
Acetate (mol/100 mol)	52.4[c]	57.2[b]	64.3[a]	1.33	0.01
Propionate (mol/100 mol)	25.3[a]	24[a]	17.7[b]	1.18	0.01
Butyrate (mol/100 mol)	14.2	12.8	13.8	0.76	0.48
Acetate: Propionate ratio	2.1[b]	2.4[b]	3.7[a]	0.20	0.01
Blood profile (portal vein)					
Glucose (mg/dL)	111.0[c]	135.7[a]	123.8[ab]	6.01	0.04
BUN (mg/dL)	14.1[b]	15.3[b]	18.1[a]	0.79	0.01
VFA (mM)	7.1	6.6	6.5	0.32	0.53
Acetate (mol/100 mol)	59.0[b]	63.3[b]	74.4[a]	2.89	0.01
Propionate (mol/100 mol)	18[a]	16[a]	11[b]	1.51	0.02
Acetate: Propionate ratio	3.4[b]	4.0[b]	6.5[a]	0.37	0.01
Blood profile (jugular vein)					
Glucose (mg/dL)	79.2[b]	93.2[a]	80.0[b]	4.27	0.06
BUN (mg/dL)	10.8[b]	10.5[b]	14.5[a]	1.05	0.03

Means within a row with different letters differ ($P < 0.05$).
[a] Dietary treatment, with barley (B), barley/sorghum (BS, 50:50) and sorghum (S) as source of starch in the concentrates.
[b] Standard error of the difference of the means.

Table 5
Production parameters in Baluchi lambs fed diets with different starch sources.

	Dietary treatment[a]			SEM[b]	P
	B	BS	S		
Initial live weight (kg)	30.5	30.1	31.2	0.81	0.60
Final live weight (kg)	45.3[b]	48.8[a]	45.7[b]	0.71	0.01
Average daily gain (kg/d)	0.21[b]	0.27[a]	0.21[b]	0.004	0.01
Feed conversion ratio (kg dry matter intake/kg gain)	9.5[a]	7.7[b]	9.7[a]	0.33	0.01

Means within a row with different letters differ ($P < 0.05$).
[a] Dietary treatment, with barley (B), barley/sorghum (BS, 50:50) and sorghum (S) as source of starch in the concentrates.
[b] Standard error of the difference of the means.

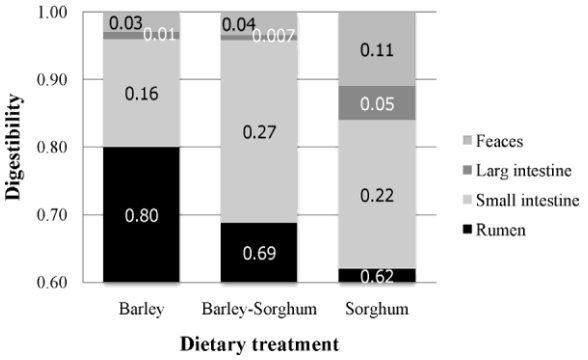

Fig. 2. Proportion of starch digestion in different segments of the gastrointestinal tract of lambs fed experimental diets with barley, barley–sorghum and sorghum as sources of starch.